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The Effects of Helmet-Mounted Display Symbology on the Opto-Kinetic Cervical Reflex and Frame of Reference

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Summary

Spatial disorientation (SD) accidents are a major contributor to the Class A mishap rate in the US Air Force. A recent investigation showed that transitions between visual meteorological conditions (VMC), when pilots use real-world visual cues to fly, to instrument meteorological conditions (IMC), when pilots have to use instruments to fly, were a leading cause of SD. In VMC, the true horizon is the primary visual cue pilots use to orient themselves. In IMC, pilots must rely on a representation of the horizon as their primary visual cue to maintain spatial orientation. Research has shown that when pilots fly in VMC, they tilt their heads in the direction opposite that of aircraft roll in an effort to keep the horizon fixed in their visual field. This implies that pilots use a world frame of reference for determining orientation. However, pilots do not tilt their heads in IMC when viewing the horizon symbol on a head-down, aircraft-referenced attitude indicator. Because pilots must transition between these two frames of reference when transitioning between VMC and IMC, this may be causing SD. The helmet-mounted display (HMD) is currently being tested as a means of displaying attitude information. The HMD symbology tested portrays a *conformal* horizon symbol which overlays the true horizon. In VMC, pilots see the true horizon and the conformal horizon symbol simultaneously. In IMC, pilots see only the horizon symbol. It was hypothesized that pilots would tilt their heads in VMC and in IMC (due to the fact that the conformal horizon represents the true horizon). Eleven pilot-subjects completed a VMC and an IMC flight task. Results showed no *practical* head tilt in either task. This was attributed to the nature of the task. Task demands determine the visual information to which pilots attend. This attention narrowing may influence the strength of the OKCR.

Introduction and Background

A recent survey of Class A mishaps occurring in 1994-1998 showed that 27% of these mishaps involved SD (Neubauer, 2000). A recent interview conducted to classify different types of SD showed that 63% of all pilots surveyed noted that the lack of a visual horizon was one of the most common contributors to SD (Sipes and Lessard, 2000). Because the horizon is the primary visual cue pilots use to orient themselves in flight, it follows that SD occurs when the horizon is not present. In VMC, pilots use the true horizon to orient themselves. In IMC, pilots must use a representation of the horizon to orient themselves. The traditional head-down instrument used for orientation is the attitude indicator (AI) and it is an aircraft-referenced display. This means that the aircraft symbol stays fixed in the center of the display and the horizon moves about it to represent aircraft attitude. The concept that attitude instruments should have an aircraft frame of reference was accepted because it was thought that pilots maintained alignment of their head and body with the aircraft. In this case, pilots are using the aircraft as their frame of reference within which they maintain their head position. Since the frame of reference is seen as fixed, the aircraft is perceived as the fixed part of

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the scene and the horizon is seen as the moving part of the scene – an aircraft frame of reference (DeHart, 1985; Weintraub and Ensing, 1992).

In 1973, Hasbrook and Rasmussen documented a head-horizon tilt phenomena that refuted the original assumption of pilot head alignment within the cockpit. They observed pilots tilting their heads to a position normal to the real horizon when making shallow and medium-banked turns during ground-oriented maneuvers. In 1989, Patterson also found that pilots were tilting their heads during visual maneuvers. Figure 1 shows the difference between the head orientation assumed of pilots in flight and the observed head

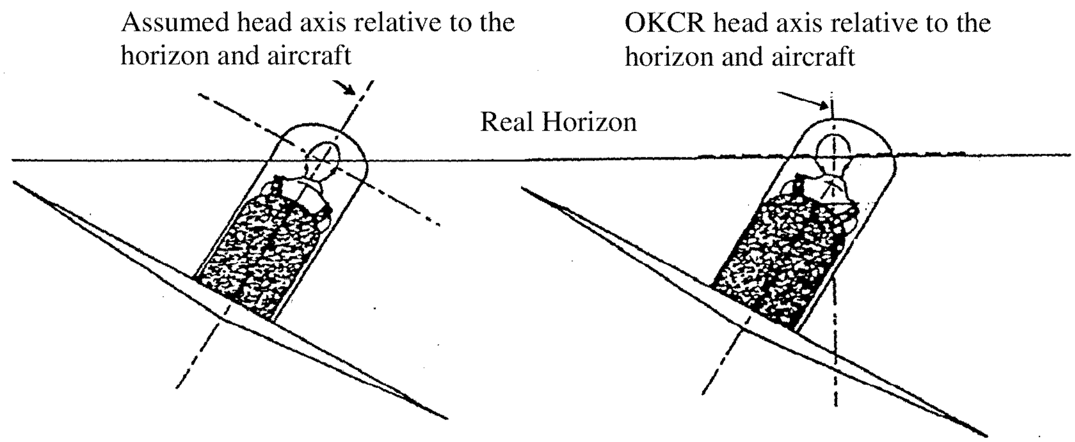

Figure 1. Head Orientations (Hasbrook and Rasmussen, 1973).

position of pilots in flight. Hasbrook and Rasmussen (1973, p. 15) speculated that "man prefers to keep his eyes normal to his visual environment". This observation makes sense because previous research has found that people naturally use the horizontal as a norm for judgment (Takala, 1951). The fact that pilots tilt their head in flight has two strong implications. First, although it was generally accepted that pilots viewed the world as stationary and the aircraft as moving when using real-world visual cues (Gillingham and Wolfe, 1985; Grether, 1947; Roscoe, 1992), this head tilt observation provides evidence for that theory. Second, the underlying assumption (pilots keep their head upright) driving the design of attitude indicators is inaccurate.

Patterson (1995, 1997) studied the phenomena more thoroughly and documented the occurrence of a visual response he termed the opto-kinetic cervical reflex (OKCR). The response causes pilots to subconsciously align their heads with the horizon. He attributed the head tilt to pilots trying to maintain a clear retinal image of the horizon while the aircraft maneuvered (Patterson, 1995, 1997). Patterson hypothesized that pilots use the horizon as their primary visual cue for determining orientation.

When pilots flew in VMC, Patterson found that pilots were tilting their heads in the opposite direction of aircraft roll, thus keeping the horizon stable on their retinas and a fixed point in their reference frame. When pilots flew in IMC (using an attitude indicator as their head-down attitude instrument in this study), no head tilt was recorded. Therefore, Patterson deduced that making a transition between the two visual cues also caused a transition in frames of reference. This switch in frames of reference causes a switch in the pilot's mental representation of the world and may be the cause of SD problems.

Since Patterson's work in 1995, additional studies have been conducted which have replicated Patterson's findings and have attempted to better characterize the head tilt response for a variety of tasks and aircraft platforms (Braithwaite, Beal, Alvarez, Jones, and Estrada (1998); Craig, Jennings, and Swail, 2000; Gallimore, Brannon, Patterson, and Nalepka, 1999; Gallimore, Patterson, Brannon, and Nalepka, 2000; Jennings, Gubbels, Swail, and Craig, 1998; Merryman and Cacioppo, 1997; Shimada, 1995; Smith, Cacioppo, and Hinman, 1997). Most notably, Merryman and Cacioppo (1997) were the first to test for and document the OKCR in actual flight. When the head tilt data from the flight test and the simulator studies

were compared, there were no significant differences among them. One of the more interesting findings relates to helicopter pilots flying profiles at night using night-vision goggles (NVGs). Braithwaite et al. (1998) conducted a study in a motion-based helicopter simulator and showed that helicopter pilots flying day missions in VMC exhibited significant OKCR. OKCR was also present when flying night missions using NVGs. As long as the true horizon was visible to pilots, regardless of whether it was visible through natural or augmented vision, head tilt occurred. Craig et al. (2000) observed this head tilt response in helicopter pilots when they used head-steered sensors to increase visibility. Jennings et al. (1998) showed the presence of the OKCR in pilots flying helicopters in low-level search and rescue missions. Gallimore et al. (1999) tested the effects of reduced FOV on the OKCR to determine if minimizing the amount of visual scene pilots saw affected the OKCR. There was no significant difference in head tilt for FOVs of 40°, 60°, and 100°. Therefore, as long as a portion (even a small portion) of the true horizon was perceived by pilots, OKCR was in effect. In addition to the military applications, a study was conducted to determine if general aviation pilots also exhibit the OKCR. Shimada (1995) used a Cessna Skyhawk to conduct his study and showed that pilots were indeed tilting their heads in the opposite direction of aircraft bank when flying in VMC.

The constant theme that persists in all of these studies is the compelling nature of the OKCR in VMC flight. The presence of the true horizon seems to be the key to eliciting the OKCR. The research has also shown that the horizon symbol on the AI was not successful in eliciting the OKCR. The newest way of presenting attitude information is via a helmet-mounted display (HMD). The HMD offers a significant advantage over the traditional AI in portraying attitude information in that pilots need not divert their attention from the outside world into the cockpit to determine exact pitch, roll, and yaw information. HMD symbology is focused at optical infinity and because of this, pilots are able to see the real world while viewing pertinent symbology. Also, attitude information on the HMD can be conformal – a symbol displayed on the HMD overlaps with the real-world feature. Therefore, when the real world is not visible, pilots can infer the location of a real-world feature by relying on the location of the symbology representing it.

On the HMD, the horizon symbol moves with the true horizon. Therefore, the HMD symbology is aircraft-referenced, just like the AI. However, unlike the AI, the symbology occupies a wider field of view (FOV), is not compressed, and is conformal with the real world. Although there have been studies conducted in which HMD symbology has been present during a VMC task (Craig et al., 2000; Jennings et al., 1998) there has never been an investigation of the effect of HMD symbology on head tilt in IMC. Therefore, it is unknown whether a conformal horizon symbol will evoke the OKCR.

Since pilots tilt their head when seeing the real world, and the HMD symbology simply exists in synergy with the outside view, one would expect the OKCR to occur in VMC when the HMD is presenting attitude information overlaid on the real world. The question is: Is the conformal HMD horizon symbol compelling enough to cause the OKCR while flying in the clouds? If pilots do tilt their heads during both VMC and IMC flying, this could potentially reduce SD.

Objectives And Hypotheses

One objective of this research was to characterize the OKCR in a VMC flight task with the true horizon present using an HMD portraying on-boresight attitude symbology. Another objective was to determine if the OKCR was also induced by the conformal horizon symbol when pilots flew in IMC using the HMD. The first hypothesis was that pilots would align their heads with the horizon in VMC flight while using the HMD. This is based on the results of the OKCR research thus far. It was also hypothesized that pilots would align their heads with the horizon symbol on the HMD.

Method

Subjects

A total of 11 pilots from Wright-Patterson Air Force Base, Shaw Air Force Base, and Springfield Air National Guard volunteered to participate in accordance with human subject requirements specified by the USAF and Wright State University. Subjects had a minimum of 100 hours of head-up display (HUD) experience.

Apparatus

The research simulator consisted of a fixed-base, single-seat, F-15 type shell with an F-15E stick (mounted on the side as in the F-16), and F-15E throttles (Figure 2). An F-16 aeromodel was employed in the simulator. A single Matsushita 21" by 16" color monitor graphically displays the head-down formats. The research facility also housed three BARCO Retrographics 801 machines that supported a 111° horizontal by 27° vertical out-the-window scene. These machines were 6.5 feet from the design eye-point.

Figure 2. Cockpit Simulator.

A Kaiser SIM EYE 40 HMD system was used to present attitude symbology projected on two combiner glasses positioned in front of the pilot's eyes. The system consisted of a helmet, an HMD, and an electrical interface unit. The HMD was binocular, portrayed monochrome symbology, had a 40° circular FOV with 100% overlap, and had 1280 x 1024 resolution. A Flock of Birds 6-D Multi-Receiver/Transmitter Tracking

Device was attached to the helmet and measured pilot's head position. A head-down display suite consisting of an up-front control (UFC) unit and three 6X8 multifunction displays (MFDs) was provided to the pilots, although the pilots did not have to interact with it to perform the tasks.

The HMD attitude symbology consisted of the MIL-STD HUD symbology set (Figure 3) which remained visible for a 30° horizontal by 20° vertical FOV. This is the FOV of a traditional HUD and was the FOV for the "virtual HUD" on the helmet for this application. The MIL-STD HUD symbology set was chosen for the current study because it includes all information required for instrument flight (U.S. Department of Defense, 1996).

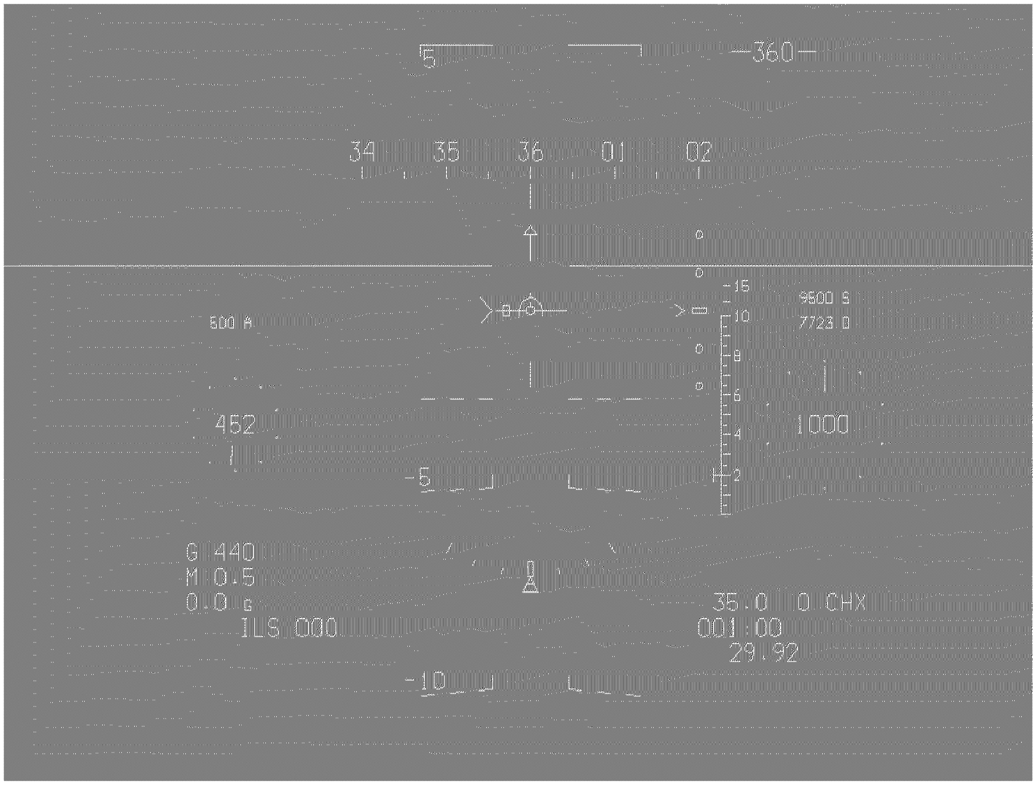

Figure 3. MIL-STD HUD Symbology (U.S. Department of Defense, 1996).

Flight Tasks and Experimental Design

Each pilot performed two tasks for data collection; a VMC flight task and an IMC flight task. The objective of both tasks was to determine if and how much pilots tilted (rolled) their head when flying with outside visual cues while using the MIL-STD HUD symbology on an HMD. In the VMC task, the HMD symbology was projected in front of the pilot's eyes, and the out-the-window scene was displayed on the BARCO projectors. In previous studies, pilots were able to choose their angle of bank to complete the prescribed task. Some pilots did not often roll above 45° - 60°, and the ones who did, did not maintain this angle of bank for a substantial period of time. Because of this, there was high variability in the data for the higher angles of bank. In the current study, an effort was made to get more data at these higher bank angles so as to better characterize the OKCR in this region. Therefore, it was decided to command pilots to certain bank angles for a specified period of time. This was accomplished via verbal instructions to pilots during the task. Pilots were also instructed to maintain a commanded altitude of 12,000 feet mean sea level (MSL) and a commanded airspeed of 400 knots. Head tilt and aircraft roll data were collected at 20 Hertz (Hz).

In the IMC task, instead of portraying an out-the-window scene on the BARCO projectors, the projectors provided a white background to simulate instrument flight conditions. Again, verbal instructions were used to indicate the commanded bank angle. Pilots were also told to maintain a commanded altitude of 12,000 feet MSL and a commanded airspeed of 400 knots. Head tilt data and aircraft roll data was collected at 20 Hz.

The study employed a within-subjects design with one independent variable and one dependent variable. The independent variable, angular aircraft bank (or roll), had 32 levels (80° right bank to 80° left bank in 5° increments). Right bank is represented with positive values and left bank is represented with negative values. The dependent variable was degree of head tilt.

Procedures

Upon arrival, the subjects were briefed on the purpose of the study and procedures for the experiment. After a consent form was signed, a standardized briefing was presented that included safety issues, details of the practice sessions, and details of the data collection sessions. An additional briefing took place once pilots were inside the cockpit, but before the HMD was donned. The mission profiles were described, the HMD was put on, and the HMD symbology was explained.

Pilots received a practice session before each data collection session. The purpose of the practice session was to allow the pilot to become familiar with the aeromodel characteristics and the symbology functionality. Each practice session contained one abbreviated mission profile similar to the data collection profile for that task. A break was offered following the first data collection run. When both data collection tasks were finished, pilots were asked to fill out a questionnaire pertaining to the study.

Results

Task I - VMC Flight Task

Each subject's data file was reorganized via computer software into five-degree categories (-80 to -76, -75 to -71, -70 to -66, . . . , 66 to 70, 71 to 75, 76 to 80) with an average head tilt value for each grouping. The result was an individual subject data file with 32 aircraft roll levels and 32 corresponding head tilt values. Linear regression analyses were conducted to determine the relationship between aircraft roll and head tilt. A check for outliers revealed four data points that were subsequently removed. The analysis showed that there was a significant linear relationship between aircraft roll and head tilt ($F(1,343) = 51.903$, $p = 0.0001$). The regression equation is:

$$\text{Head Tilt} = 0.3651 - 0.00892\,(\text{Aircraft Roll});\ \text{Adjusted } R^2 = 0.13$$

A lack of fit test was also conducted to ensure that the relationship between the two variables was linear. The test showed no lack of fit of the linear relationship ($F(30,313) = 1.09$, $p = 0.3443$). Figure 4 shows the average value of head tilt at each aircraft bank category.

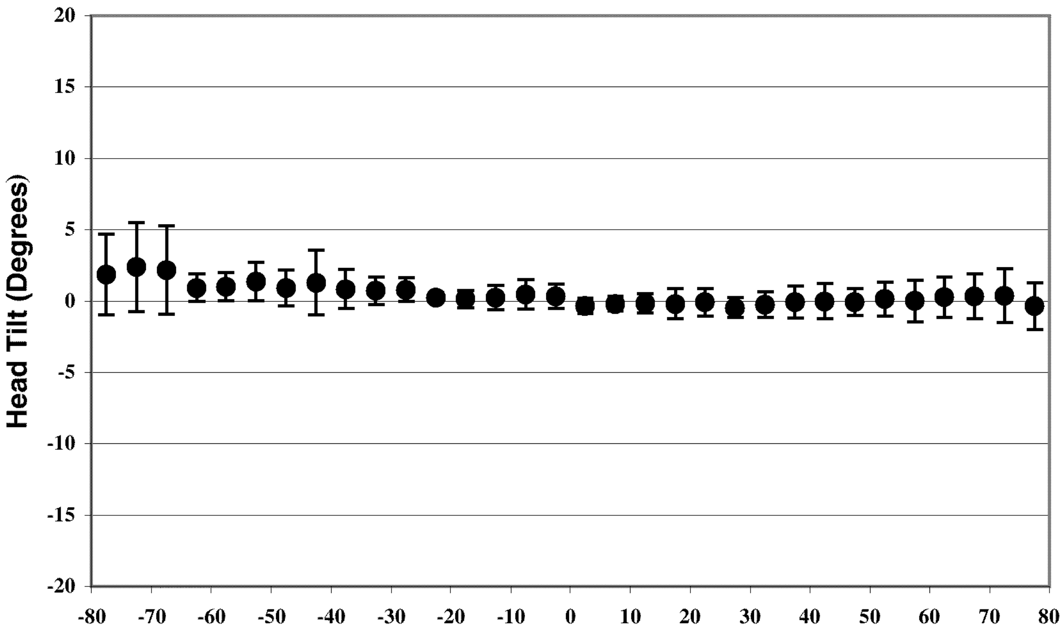

Figure 4. VMC Task – Average Head Tilt (Error bars represent standard deviation).

An analysis of variance showed a statistically significant difference between specific levels of aircraft roll in terms of head tilt (F(31,313) = 2.74, p = 0.0001), however, the regression analysis verifies that the relationship is linear with a very small slope (0.009) and a maximum head tilt value at $\pm$1.085°. Based on previous studies, head tilt angles of less than three degrees were considered not to have real world practical significance because of potential aircraft vibration induced head movement, as well as random/natural head movement.

IMC Flight Task

Manipulation of the data for the IMC Task was identical to that of the VMC Task. After checking for outliers and assuring compliance of the linear regression analysis assumptions, the regression analysis showed a significant linear relationship between aircraft roll and head tilt (F(1,349) = 19.756, p = 0.0001). This linear relationship was confirmed by an insignificant lack of fit test (F(30,319) = 0.86, p = 0.688). The regression equation is:

$$\text{Head Tilt} = 0.1974 - 0.00375 \text{ (Aircraft Roll); Adjusted } R^2 = 0.05$$

Again, the analysis of variance showed a *statistically* significant difference between specific levels of aircraft roll in terms of head tilt (F(31,319) = 1.46, p = 0.0595), but there is no *practical* significance in head roll angles of three degrees or less. Figure 5 shows the average head tilt for each aircraft bank category.

Discussion

The OKCR has been shown to exist in numerous studies (Braithwaite et al., 1998; Craig et al., 2000; Gallimore et al., 1998; Gallimore et al., 2000, Jennings et al., 1998; Merryman and Cacioppo, 1997; Patterson, 1995; Patterson et al., 1997; Smith et al., 1997), however, it is clear from the results section that subjects in this study did not exhibit the OKCR.

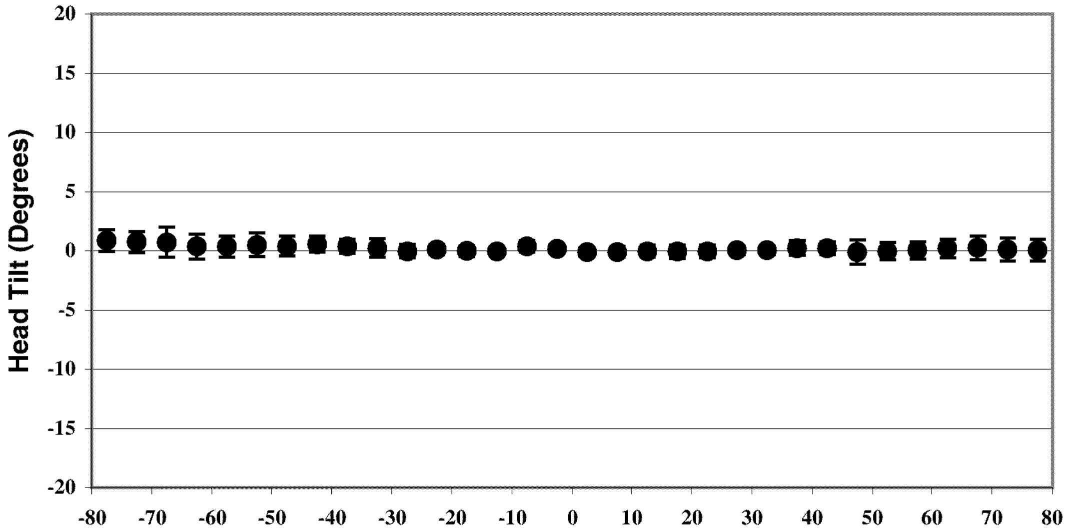

Figure 5. IMC Task – Average Head Tilt (Error bars represent standard deviation).

VMC Task Discussion

The most likely reason why subjects did not tilt their heads during this task was because of the nature of the task. In the previous studies, the VMC task consisted of pilots flying ground-oriented tasks: low-level flight, looking outside for waypoints, flying along rivers, etc. Pilots were not told specific bank angles to maintain; they were flying under less controlled and more realistic conditions. Hasbrook and Rasmussen (1973) observed the head-horizon tilt phenomena when pilots performed figure eights around pylons or S-turns over a road – both ground-oriented tasks. Head tilt, thus far, has been found to be present when pilots are actively viewing the real world and attending to its features. Pilots tilted their head to keep the horizon stationary in their visual field to maintain their orientation.

In the current study, subjects were flying at a high altitude (12,000 feet MSL) and were instructed via verbal command to bank their aircraft to a certain degree and maintain that angle of bank until they were told to level out. They were also instructed to maintain a commanded airspeed and altitude. To perform these tasks, pilots had to *attend to their instruments, not the horizon*; therefore the task strictly became an instrument-oriented task, not a ground-oriented one.

To complete the VMC task, the key portion of MIL-STD HUD symbology used was the bank scale (see Figure 3). This instrument functions such that the scale stays fixed and the pointer moves as the aircraft banks. Pilots determine their degree of bank, by reading the pointer position against the scale marking. In terms of figure-ground relationships, it is natural for pilots to keep the ground (the bank scale) fixed so they can accurately read the position of the figure (the pointer) against the ground (Goldstein, 1996). Therefore, keeping the scale fixed meant keeping the head upright – head movement might cause pilots to misread their bank angle.

In trying to maintain the commanded airspeed and altitude, an upright head position facilitated the accurate reading of the clock representations of airspeed and altitude, and the digital readout, which appeared in the center of the clocks. Tilting their heads could have caused an increase in time to recognize the airspeed and altitude information. This is confirmed by Friedman and Hall (1996), who found a linear relationship between time to recognize a stimulus and the distance of the stimulus from an upright position.

To summarize, pilots used bank, airspeed, and altitude information to perform this task. The symbology was designed to be interpreted when pilots are looking straight ahead with their head upright. Any head movement might cause one to not see symbology or to see it improperly. Therefore, pilots in the current study may have been actively keeping their heads in line with the symbology to allow them to interpret its information more efficiently – correct interpretation of the symbology facilitates spatial orientation. *The premise that pilots align their head with the cue that allows them maximum orientation information is a valid one in light of these results and what is known about the OKCR.*

IMC Task Discussion

Although it was hypothesized that the horizon *symbol* on the HMD might cause head tilt, this was not supported in the data. Because the IMC task was the same as the VMC task, subjects were focusing on the HMD symbology set to perform their task. The subjects may have been again focusing on the bank scale, not the horizon symbol. Central foveal vision is only 2° and although the horizon symbol was in their parafoveal view, subjects did not need to attend to that symbol to maintain orientation. They knew from their bank scale what their roll angle was. A quick crosscheck of the pitch scale gave them pitch information. Pilots were using the symbology to maintain orientation; therefore, they kept their head aligned with their primary orientation information.

General Discussion

There has been extensive research conducted on attention and HUD tasking, and limited research with respect to attention and HMDs. For example, Wickens and colleagues (Martin-Emerson and Wickens, 1997; Ververs and Wickens, 1998; Wickens and Long, 1995; Yeh, Wickens, and Seagull, 1999) showed that some tasks do not allow for the near domain (symbology) and the far domain (real world) to act synergistically. Similarly, McCann, Foyle, and Johnston (1993) supported two interesting theories pertaining to attentional demands and HUDs. First, parallel processing of non-conformal information on the HUD and information from the outside world is difficult for pilots to accomplish. Second, and more specific to the current research, a shift in attention was necessary to transition from the HUD information to the outside-world visual information. Only true divided attention tasks, (i.e., tracking a commanded path using instruments while looking for targets in the real world scene) support the knowledge of both domains. The task performed in the current study was definitely a focused attention task. Pilots could complete the task by focusing only on the symbology.

Conclusions

Knowledge of the interaction between attention and frame of reference may help reduce spatial disorientation incidents in two ways. First, when transitions between frames of reference are not necessary, channeling pilots' attention to specific information may eliminate casual or unintentional transitions, which may cause disorientation. Second, when transitions between frames of reference are necessary, facilitating the transitions via appropriate symbology designs will make the transitions as smooth as possible.

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